Cetaceans and Naval Sonar: Behavioral Response as a Function of Sonar Frequency

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Award Number: N00014-08-1-0984
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LONG-TERM GOALS

Data on the responsiveness of free-ranging cetaceans to mid-frequency sonar signals are lacking, with only a few species having been studied in relation to a few types of sonar signals, mostly SURTASS-LFA (Nowacek et al., 2007). This specific project was initially motivated by observations of possible killer whale (*Orcinus orca*) reactions to sonars, in the Vestfjord basin of Norway and the USS Shoup incident in Haro Strait in Washington State (WWF-Norway, 2001; NMFS, 2005). While those incidents have not led to observation of strandings or direct mortality, the perceived behavioral changes in response to sonar have negatively impacted the public image of the Navies involved, and may have harmed the stakeholder community that works with killer whales.

The hypothesis explored in this research program is that strong difference in hearing sensitivity of killer whales at the two sonar frequencies influences their behavioral reactions. Using all available hearing data from captive animals, our research team produced a composite killer hearing curve (Fig 1). It can be clearly seen that killer whale hearing seems to be 20-25dB less sensitive at 1-2 kHz than at 6-7 kHz. The term “sensation level” refers not to absolute intensity of a sound, but intensity relative to the hearing threshold for that sound for a given individual. Acoustic criteria recommend use of sensation level to estimate physiological impacts on hearing (Southall et al., 2007), but the specific influence of hearing sensitivity on the risk of *behavioral* effects has never been directly assessed.

OBJECTIVES

This research program, begun 01 July 2008, seeks to more fully quantify behavioral response of cetaceans to sonar as a function of the frequency band utilized by the sonar. A second objective of the research program is to continue to monitor the movements and behavior of killer whales in relation to future FLOTEX naval exercises, if possible. The project is motivated both by the applied need to assess the environmental impact of a new lower-frequency sonar system and the basic science question of the influence of sonar frequency on behavioral effects on marine mammals. We seek to test the prediction that the aversive-ness, or behavioral impact, of a sound should be influenced by the hearing sensitivities of species at the relevant sonar frequency. For species where little information is available

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Cetaceans and Naval Sonar: Behavioral Response as a Function of Sonar Frequency**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of St Andrews,Sea Mammal Research Unit,St Andrews, KY16 8LB United Kingdom,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

on hearing sensitivities, behavioral responsiveness as a function of frequency will provide quantitative data on the effect of frequency.

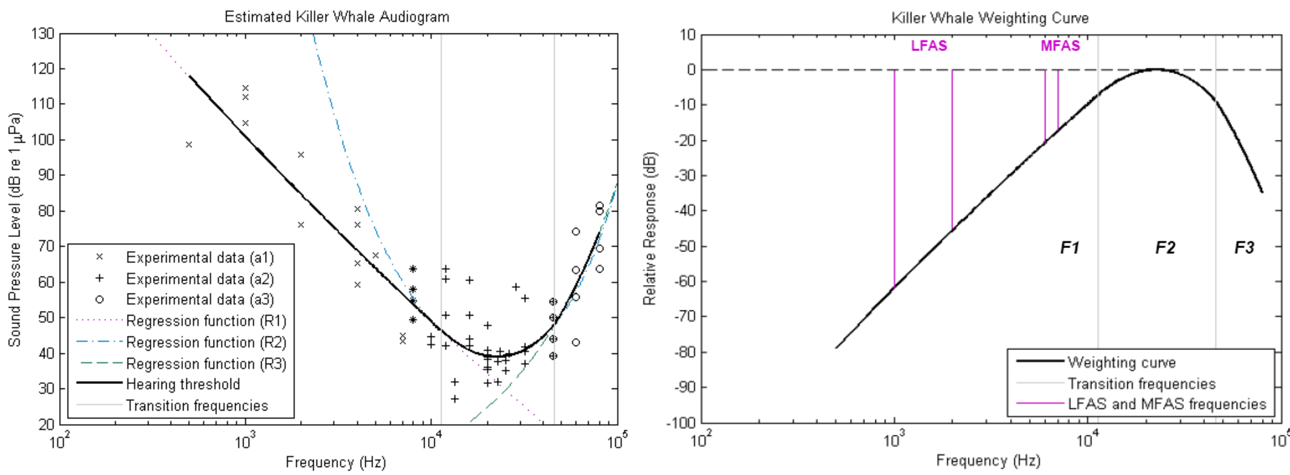

Fig 1. Left: An estimated audiogram for the killer whale using non-linear regression on all published hearing threshold data. Three separate functions were fit over the full frequency range of killer whale hearing. Right: weighting curves to convert received levels to "sensation levels" weighted by the hearing threshold. Note that killer whales have reduced hearing sensitivity to the 1-2 kHz "LFAS" signal compared to the 6-7 kHz "MFAS" signal.

APPROACH

Our primary approach to achieve the objectives was to conduct controlled presentations of military sonar signal sequences at 2 different frequencies (1-2 kHz and 6-7 kHz) in blocks and relevant control sounds while observing their behavior using tags, towed hydrophone arrays, and visual observations. Specific research tasks are: 1) Determination of behavioral response thresholds by approaching a tagged whale while transmitting sonar signals. Each tagged whale is sequentially tested at both sonar frequencies, in random order, with no-sound approaches or playback of killer-whale calls included as practicable as negative and positive controls*;* 2) Description of behavior during sonar exposures versus baseline and controls, and interpretation of the biological significance of any observed behavioral change. Careful monitoring and mitigation protocols are followed to reduce risk of harm to all research subjects; 3) Exploration of how response thresholds vary at different sonar frequencies, and in relation to reported hearing thresholds at the tested frequencies. Because we have better data on hearing sensitivity for killer whales, they have been the primary study species, but experiments with pilot and sperm whales enable a fuller comparative analysis of behavioural reaction thresholds.

The research is carried out by an international collaborative team from the Sea Mammal Research Unit (SMRU), Woods Hole Oceanographic Institution (WHOI), Norwegian Defense Research Establishment (FFI), Institute of Marine Research (IMR), and Netherlands Organization for Applied Scientific Research (TNO).

WORK COMPLETED

This research grant expired in June, 2011. Data collection was completed for this project in the summer of 2009, and the final year was primarily spent on data processing and analyses to achieve the project objectives. All of the 3S experiments have been carefully described, with presentations of the complex suite of behavioural, environmental, and acoustic features of each experiment documented in a comprehensive technical report (Miller et al., 2011). The report has been released by the Scottish Oceans Institute and is available at the following web address:
http://soi.st-andrews.ac.uk/pageset.aspx?psr=443

As is fully detailed in the technical report, the final dataset consists of 14 experiments with three cetacean species. Based upon the behavioural changes observed during the experiments, independent panels within the 3S research team has categorized these putative effects of the sonar into severity classes based upon the behavioural response scale proposed by Southall et al. (2007). The potential influence of sonar frequency was examined as part of the analysis (see below). This output is currently in draft form for submission for peer-review under the title, **'The severity of behavioural changes observed during experimental exposures to sonar',** with submission expected by the end of 2011.

In addition to the broad descriptive analysis of the substantial 3S dataset, we have prepared a manuscript entitled **Quantifying effects of sonar on cetaceans: dose-response relationships for avoidance of sonar by free-ranging killer whales,** which is currently in revision. In this paper, we treat the 3S experiments as clinical dose-escalation trials, in which the goal is to describe the dose-response relationship of avoidance reactions to sonar. For each exposure conducted, we determined whether or not a response took place using objective criteria supported by quantitative analyses, and the received level and distance from the sonar for each documented reaction. Based upon the observed thresholds, dose-response functions have been developed, and the influence of factors such as sonar presentation order and sonar frequency can be quantitatively examined.

In addition to those core outputs focused on the project goals, a number of additional works are in various stages of preparation for publication in peer-review journals.

Due to changes in location and timing, we were not able to monitor any additional FLOTEX exercises.

RESULTS

Dataset: The combined 3S cetacean CEE data set totals 4 killer whales, 4 sperm whales, and 6 pilot whales, and is well-balanced in terms of sonar frequencies presented to the whale. We have also achieved 14 playbacks of natural killer whale sounds (*orca*), including 2 that were completed during the baseline research trial in Iceland and 4 during the 2010 baseline trial in Norway. Baseline data to better describe the natural behavior of the study species and to make comparisons to the experimental datasets (Miller et al., 2009) was collected under award N000141010355. Details of the results of the killer whale playbacks are given in the report under award number N000141010355.

The severity of behavioral changes observed during experimental exposures to sonar: Based upon the rich descriptive narration and plots presented in the 3S technical report, 2 teams of scientists scored the severity of behavioral changes observed during sonar exposures, and the 2 teams met with a moderator to achieve a consensus. Behavioral changes were judged during sonar exposures, and also during the control exposures which were silent passes of the source vessel towing the source but not

transmitting the sonar, and playback of killer whales sounds (Fig. 2). These results suggest that the rate of low-severity change (1-3) were roughly equivalent across the different exposure types, but that the rate of more severe changes (4-8) was notably greater in the sonar and orca exposures than during the silent controls. This is important as it suggests that the more severe behavioral changes were indeed reactions to the sonar.

Severity Score	SILENT control	6-7 kHz upsweep	1-2 kHz upsweep	1-2 kHz down-swp	*orca* playback
9					
8		X			
7		XX	XX		
6		XXX	XXXXX	XXXXXXX X	XXX
5	XX	XXXXX	XXX	XX	XXX
4	X	XX	XXXXXX	XXXXXXX XXX	XXXXXX
3	XXX	XX	XX	XXXX	X
2		X	X		XXX
1	X	X	XX	XX	X
0	X	XXX	X		X

Fig 2. The number of behavioral changes classified by their severity (using Southall, 2007), and the type of presentation (control, sonar signal type, or orca playback). Note that, for comparison purposes, the number of changes 'x' shown here were weighted by the total number of exposure sessions of each type.

A total of 84 behavioral changes were judged to have occurred during the sonar exposures, roughly equally distributed across the three species (Fig 3). Of these behavioural changes, avoidance was the most common, though changes to diving, vocal, and social behavior were also noted. The single most severe event (severity score of 8) was a prolonged separation of a dependent offspring from its group in an MFAS exposure to killer whale group oo08_149a. The calf was seen alone for the first time part-way through the MFAS exposure. This triggered a mitigation stop to the sonar transmissions, which coincided with the scheduled end of the exposure period. During the sonar transmission period, the tagged group produced a number of high-frequency whistles (Samarra et al., 2010). The wide difference in frequency of these whistles and the sonar may indicate that the sonar caused some disruption of acoustic reunion mechanisms. The calf rejoined the group after 86 min and post-experiment monitoring confirmed that the animal was closely travelling with its group for several hours following the exposure. A total of 5 behavioral changes were judged to have severity of 7, and consisted of cessation of foraging, or avoidance that persisted substantially longer than the sonar transmission period.

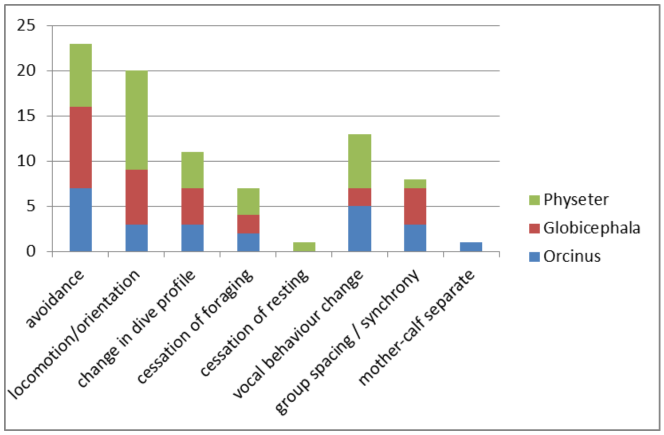

Fig 3. The number of different classes of behavioral changes observed during the 3S experimental exposures.

An important feature of the Southall et al. (2007) severity scale is that the received sound pressure level (SPL) of the sonar is linked to the reported response. The 3S experiments were designed to escalate the received level of the sonar starting with a low 152 dB source-level signal transmitted at 7-8km range. The source level was ramped-up over a 10 minute period, and the vessel then approached the tagged whale. This resulted in whales being exposed to pings estimated at received levels from <90dB to 180dBrms re 1µPa. Inspection of the results (Fig 4) indicates that behavioral changes observed during the 3S sonar exposures started over a wide range of received levels. A number of changes occurred at levels <99dB, while others occurred at received levels >170dB. Interestingly, killer whales had the most severe changes, also at lower received SPL than the other target species.

Severity Score	<99 dB	100-109	110-119	120-129	*130-139*	140-149	150-159	160-169	170-179	180-189
9										
8							O			
7	OO				OO		G			
6	OO			GPP	P	GP	OGG PP	OP		
5	O?		OG		O	O	OOG GG	O		
4	G			PP		GPPP	GGP P	PPP	G	G
3					O	OOP	GP	GG		
2			O				OP			
1			P		P	P	GP			

Fig 4. Observed behavioral changes for each species (O=orcinus; G= globicephala; P=physeter) scored by severity and the received SPL at the start of the behavioral change.

One of the primary objectives of the research was to investigate the influence of sonar frequency on the likelihood of behavioral reaction occurring in response to sonar signals. In the 3S experiments, both 1-2 kHz and 6-7 kHz sonar signals were transmitted in separate exposure sessions. Because the hearing of odontocetes becomes less sensitive below 6kHz, we would predict that behavioral reactions to sonar would occur at lower received levels if sensation level (defined as level above the auditory threshold) was an important predictor of response. Interestingly, there was no clear difference in the distribution of behavioral changes with respect to sonar frequency up to 159dB received SPL, which was the maximum received level obtained during any 6-7 kHz exposure session. This indicates that sensation level may not be a particularly good predictor of when behavioral responses start.

Severity Score	<99 dB	100-109	110-119	120-129	*130-139*	140-149	150-159	160-169	170-179	180-189
9										
8							M			
7	LL				MM		L			
6	LM			MML	M	LL	LLL LL	LL		
5	LL		MM		M	M	MLL ML	L		
4	M			LL		LLL L	LLL M	LLL	L	L
3					M	MML	LL	LL		
2			M				LL			
1			L		L	L	ML			

Fig. 5. Behavioral changes during exposure to 2 sonar frequencies (L = 1-2kHz; M = 6-7kHz) scored by severity and maximum received SPL before the behavioral change. Note that no 6-7 kHz exposures were conducted above the 150-159dB range of received levels.

Dose-response relationships in the killer whale: Avoidance reactions were clearly observed in 6 of the 8 experimental exposures to killer whales, and typically entailed increases in speed, changes of direction or change to more directional movement, and movement sideways to the approach path of the source vessel. We specified the moment in time when the reaction started using the track data and detailed inspection of the Dtag record. The highest received level before the reaction started was used as the threshold of the response. In the 2 cases where no response was observed, the reaction threshold is assumed to be above maximum level to which the group was exposed.

These observed thresholds were fit to a Bayesian dose-response model, which explicitly captures any possible effect of sonar frequency (MFAS vs LFAS) and whether or not the sonar had been previously exposed to the sonar using the following response function for the mean reaction threshold of each individual whale:

$$\mu_{ij} = \mu_i + \beta_1 I(exposure) + \beta_2 I(MFAS)$$

The distribution of mean thresholds across different whales gives the fitted population dose-response function. By analyzing our experiments in this fashion, therefore, we are able to develop predicted dose-response functions for specific types of behavioral reactions. Here, we only present the analysis versus the received sound pressure level (Fig. 6). The dose response curve indicates a risk of response down to rather low received sound pressure levels reflected our observation of some avoidance reactions at rather low levels (<99dB re 1μPa; see Fig. 4). Received sound pressure was not the only 'dose' factor that varied in our exposure sessions, and we are also evaluating the dose-response relationships for sensation level and distance from the source, which are also likely to influence reactions to sonar.

The Bayesian dose-response analysis explicitly evaluates the influence of previous exposure and sonar frequency on the dose-response function. Thus, is also a powerful tool for assessing whether response thresholds are influenced by hearing sensitivity (Fig 1). Indeed, consistent with the results from the severity scoring analysis, there is little indication that sonar frequency had a strong influence on the received sound pressure level at which killer whales started to avoid the sonar source, Though there is a slight tendency for avoidance of MFAS 6-7 kHz sonars to start at lower received sound pressure levels than LFAS 1-2 kHz (Fig. 7, right), the difference is much less than the 20-25 dB difference in hearing thresholds of those frequencies. Also, whether or not a subject had been previously exposed to a sonar signal had little influence on the threshold at which avoidance reactions started (Fig 7, left).

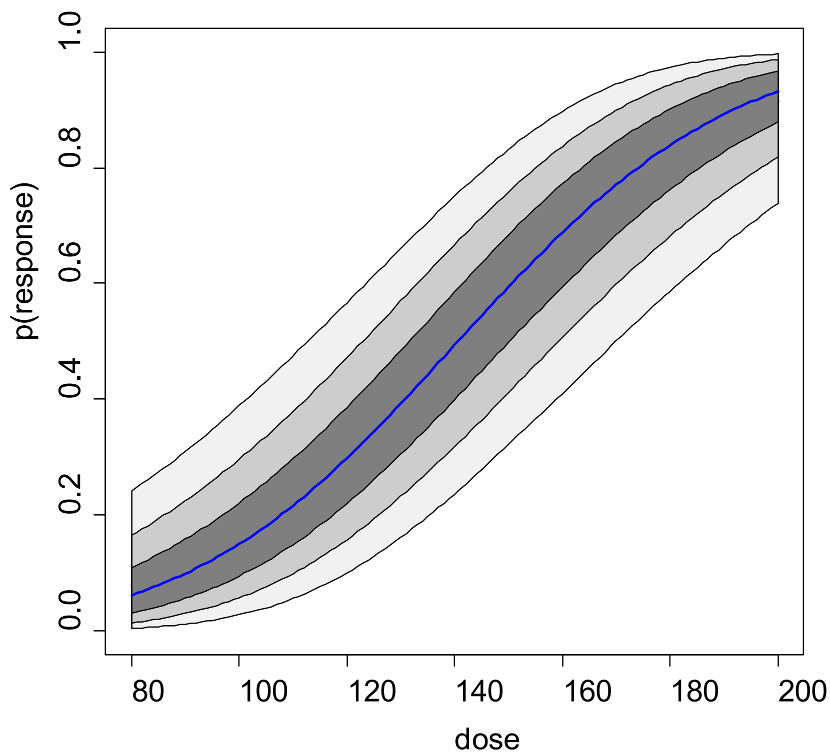

Fig 6. The probability of an avoidance response occurring in killer whales as a function of the received sound pressure level in dB re 1μPa ('dose') to which it was exposed, assuming a 1-2 sonar signal. The bands represent 95%, 80% and 50% confidence intervals.

In the 2006 FLOTEX exercises in Vestfjord, we documented that the number of killer whales seen in the whale-watching area dropped in the 2 days after sonar transmissions started, followed by 3 days

with no whales seen (Kvadsheim et al., 2007). The results of our experiments are consistent with the conclusion that the decline in numbers could, indeed, have been due to the sonar activity during the FLOTEX trial (Miller et al., submitted).

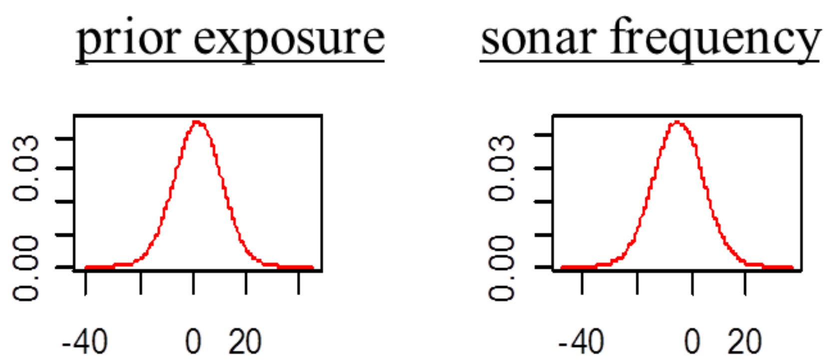

Fig. 7 The influence of prior exposure (left) and sonar frequency (right) on the threshold at which avoidance started in killer whales.

To conclude, we feel that the research conducted under award N00014-08-1-0984 has been effective at achieving the goals of understanding whether and how cetaceans respond to sonar, and how sonar frequency might influence the responsiveness of the target species.

IMPACT/APPLICATIONS

The establishment of a dose:response function for the avoidance responses of killer whales exposed to sonar signals will be useful for implementatin of regulations regarding exposure of marine mammals to sounds.

RELATED PROJECTS

The research under this award will be continued under award number N000141010355.

PATENTS

There are no patents associated with this award.

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